Annihilation Contribution to $B \to a_1(1260)(b_1(1235))K^*$ Decays

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Abstract

Within the framework of perturbative QCD approach, we study the charmless two-body decays $B \to a_1(1260)K^*, b_1(1235)K^*$. Using the decays constants and the light-cone distribution amplitudes for these mesons derived from the QCD sum rule method, we find the following results: (a) Our predictions for the branching ratios are consistent well with the QCDF results within errors, but much larger than the naive factorization approach calculation values. BarBar has searched the decays $B \to a_1^- \bar{K}^{*0}, b_1 K^*$ and set the upper limits for their branching ratios, which are (much) lower than our predictions. The current data seem to imply that penguin annihilation is small in these penguin-dominated decays. Certainly, if the factorizable annihilation diagram contributions are turned off, the branching ratios will fall dramatically and many of them reduced by more than half. It needs further accurate experiments to clarify the differences between the theoretical predictions and the present upper limits. (b) We predict that the similar anomalous polarizations occured in decays $B \to \phi K^*$ also happen in decays $B \to a_1 K^*$, while not happen in decays $B \to b_1 K^*$. Here still the contributions from the annihilation diagrams play an important role to explain the lager transverse polarizations in decays $B \to a_1 K^*$, while are not sensitive to the polarizations in decays $B \to b_1 K^*$. (c) Our predictions for the direct CP-asymmetries agree well with the QCDF results within errors. The decays $\bar{B}^0 \to b_1^+ K^{*-}, B^- \to b_1^0 K^{*-}$ have larger direct CP-asymmetries, which could be measured by the present LHCb experiments.

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I. INTRODUCTION

In general, the mesons are classified in J^{PC} multiplets. There are two types of orbitally excited axial-vector mesons, namely 1^{++} and 1^{+-}. The former includes $a_1(1260), f_1(1285), f_1(1420)$ and K_{1A}, which compose the $^3P_1$-nonet, and the latter includes $b_1(1235), h_1(1170), h_1(1380)$ and K_{1B}, which compose the $^1P_1$-nonet. There is an important character for these axial-vector mesons except $a_1(1260)$ and $b_1(1235)$, that is each different flavor state can mix with one another, which comes from the other nonet meson or the same nonet one. There is not mix between $a_1(1260)$ and $b_1(1235)$ because of the opposite C-parities. They do not also mix with others. So compared with other axial-vector mesons, these two mesons should have less uncertainties about their inner structures.

Like decay modes $B \to VV$, the charmless decays $B \to a_1(1260)K^*, b_1(1235)K^*$ also have three polarization states and so are expected to have rich physics. In many $B \to VV$ decays, the informations on branching ratios and polarization fractions among various helicity amplitudes have been studied by many authors [1–4]. Through polarization studies, some underling helicity structures of the decay mechanism are proclaimed. They find that the polarization fractions follow the naive counting rule, that is $f_L \sim 1 - O(m_V^2/m_B^2), f_\parallel \sim f_\perp \sim O(m_V^2/m_B^2)$. But if the contributions from the factorizable emission amplitudes are suppressed for some decay modes, this counting rule might be modified in some extent even dramatically by other contributions. For example, many anomalous longitudinal polarization fractions in the decays $B \to \rho K^*, \phi K^*$ have been measured by experiments, which are about 50% [5], except that of the decay $B^- \to K^{*-}\rho^0$ with large value $(96^{+6}_{-16})\%$ [5] (the newer measurement is $(90 \pm 20)\%$) [6]. The branching ratios of the decays $B^- \to \rho^-\bar{K}^{*-}$ and $B \to \phi K^*$ have been measured by experiments which are near 10.0×10^{-6} [5], and that of the decay $\bar{B}^0 \to \bar{K}^{*0}\rho^0$ is smaller and about $(3.4 \pm 1.0) \times 10^{-6}$ [5]. Whether the similar results also occurs in the $B \to a_1(1260)K^*, b_1(1235)K^*$ decay modes is worth researching by theories and experiments. We know that $a_1(1260)$ has some similar behaves with the vector meson, so one can expect that there should exist some similar characters in the branching ratios and the polarization fractions between decays $B \to a_1(1260)K^*$ and $B \to \rho K^*$, where $a_1(1260)$ is replaced by its scalar partner ρ. While it is not the case for $b_1(1235)$ because of its different characters in decay constant and light-cone distribution amplitude (LCDA) compared with those of $a_1(1260)$. For example, the longitude decay constant is very small for the charged $b_1(1235)$ states and vanishes under the SU(3) limit. It is zero for the neutral $b_1^0(1235)$ state. While the transverse decay constant of $a_1(1260)$ vanishes under the SU(3) limit. In the isospin limit, the chiral-odd (-even) LCDAs of meson $b_1(1235)$ are symmetric (antisymmetric) under the exchange of quark and anti-quark momentum fractions. It is just contrary to the symmetric behavior for $a_1(1260)$. In view of these differences, one can expect that there should exist very different results between $B \to a_1(1260)K^*$ and $B \to b_1(1235)K^*$. On the theoretical side, $B \to a_1(1260)K^*, b_1(1235)K^*$ decays have been studied by Cheng and Yang in Ref. [7] where the branching ratios are very different with those calculated by the naive factorization approach [8]. To clarify such large differences is another motivation of this work. On the experimental side, only the upper limits for some of the considered decays can be available [9, 10].

In the following, $a_1(1260)$ and $b_1(1235)$ are denoted as a_1 and b_1 in some places for convenience. The layout of this paper is as follows. In Sec.II, we analyze these decay

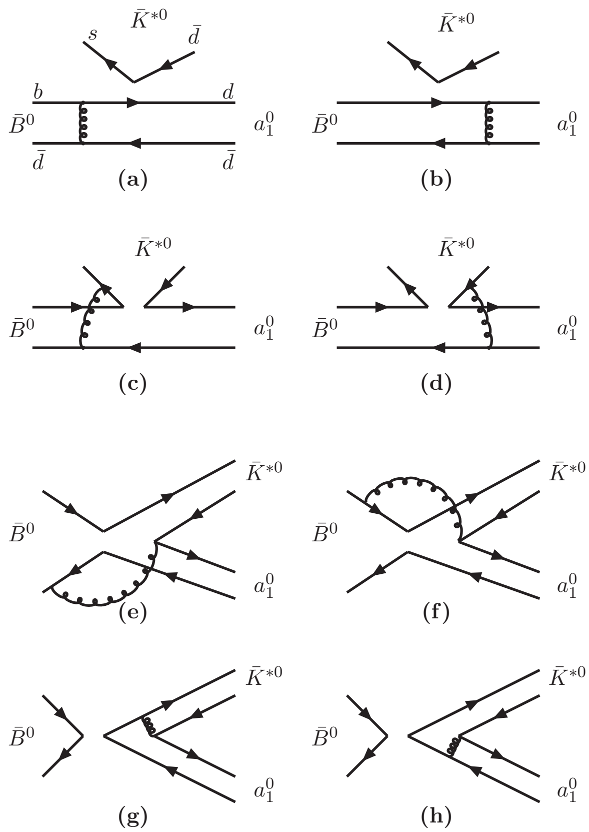

FIG. 1: Diagrams contributing to the decay $\bar{B}^0 \to a_1^0 \bar{K}^{*0}$.

channels using the PQCD approach. The numerical results and the discussions are given in Sec. III. The conclusions are presented in the final part.

II. THE PERTURBATIVE QCD CALCULATION

The PQCD approach has been proved been an effective theory to handle hadronic B decays in many works [2, 3, 11, 12]. Because of taking into account the transverse momentum of the valence quarks in the hadrons, one will encounter double logarithm divergences when the soft and the collinear momenta overlap. Fortunately, these large double logarithm can be re-summed into the Sudakov factor [13]. There are also another type of double logarithms which arise from the loop corrections to the weak decay vertex. These double logarithms can also be re-summed and resulted in the threshold factor. This factor decreases faster than any other power of the momentum fraction in the threshold region, which removes the endpoint singularity. This factor is often parameterized into a simple form which is independent on channels, twists and flavors [14]. Certainly, when the higher order diagrams only suffer from soft or collinear infrared divergence, it is ease to cure by using the eikonal approximation [15]. Controlling these kinds of divergences reasonably makes the PQCD approach more self-consistent.

Here we take the decay $\bar{B}^0 \to a_1^0 \bar{K}^{*0}$ as an example, whose part of diagrams are shown in Figure 1. These eight Feynman diagrams belong to the condition of $\bar{K}^{*0}$ meson being at the emission position. For the factorizable and nonfactorizable emission diagrams 1(a),

1(b) and 1(c), 1(d), if one exchanges the positions of a_1^0 and $\bar{K}^{*0}$, the corresponding diagrams can also contribute to the decay. All of these single hard gluon exchange diagrams contain all of the leading order contributions to $\bar{B}^0 \to a_1^0 \bar{K}^{*0}$ in the PQCD approach. The amplitudes of diagrams 1(a) and 1(b) are denoted as F_{ea_1}. If $d(\bar{d})$ quark in meson a_1^0 ($\bar{K}^{*0}$) of each diagram in Fig.1 is replaced with $u(\bar{u})$ quark, we can get the Feynman diagrams for the decay $\bar{B}^0 \to a_1^+ K^{*-}$. It is ease to think that the decay $\bar{B}^0 \to a_1^+ K^{*-}$ would receive larger tree operator contributions than the decay $\bar{B}^0 \to a_1^0 \bar{K}^{*0}$. If $\bar{d}$ quark in meson a_1^0 ($\bar{B}^0$) of each diagram in Fig.1 is replaced with $\bar{u}$, we can get the Feynman diagrams for the decay $B^- \to a_1^- \bar{K}^{*0}$. Compared with the decay $B^- \to a_1^- K^{*0}$, $\bar{B}^0 \to a_1^0 \bar{K}^{*0}$ and $B^- \to a_1^0 K^{*-}$ have extra contributions from the the factorizable and nonfactorizable emission diagrams. It is similar to the decay modes $B \to K^* \rho$ [2], both longitudinal and transverse polarizations can contribute to the decay width. So we can get three kinds of polarization amplitudes M_L (longitudinal) and $M_{N,T}$ (transverse) by calculating these diagrams. Because of the aforementioned distribution amplitudes of the axial-vectors having the same formats as those of the vectors except a factor, so the formulas of here considered decays can be obtained from the ones of $B \to VV$ decays by some replacements. Certainly, there also exists a difference: if the emitted meson is b_1 for the factorizable emission diagrams, the amplitude F_{eb_1} contributed by the $(V-A)(V \pm A)$ operators would be zero due to the vanishing decay constant f_{b_1}. Here for our considered decays, the amplitude for the factorizable annihilation diagrams F_{aa_1} (if a_1 meson is replaced with b_1, the amplitude is denoted as F_{ab_1}) plays an important role. To calculate accurately them will have an important effect on the branching ratios and the polarization fractions.

III. NUMERICAL RESULTS AND DISCUSSIONS

For the wave function of the heavy B meson, we take

$$\Phi_B(x, b) = \frac{1}{\sqrt{2N_c}} (\not{P}_B + m_B) \gamma_5 \phi_B(x, b). \tag{1}$$

Here only the contribution of Lorentz structure $\phi_B(x, b)$ is taken into account, since the contribution of the second Lorentz structure $\bar{\phi}_B$ is numerically small [16] and has been neglected. For the distribution amplitude $\phi_B(x, b)$ in Eq.(1), we adopt the following model:

$$\phi_B(x, b) = N_B x^2 (1-x)^2 \exp[-\frac{M_B^2 x^2}{2\omega_b^2} - \frac{1}{2}(\omega_b b)^2], \tag{2}$$

where ω_b is a free parameter, and taken as $\omega_b = 0.4 \pm 0.04$ Gev in numerical calculations, and $N_B = 91.745$ is the normalization factor for $\omega_b = 0.4$.

In these decays, both the longitudinal and the transverse polarizations are involved for each final meson. Their decay constants, Gegenbauer moments and wave functions are the same with those in Ref. [17]

We use the following input parameters in the numerical calculations [18, 19]:

$$\begin{aligned} f_B &= 190MeV, M_B = 5.28GeV, M_W = 80.41GeV, &(3)\\ \tau_{B^\pm} &= 1.638 \times 10^{-12}s, \tau_{B^0} = 1.525 \times 10^{-12}s, &(4)\\ |V_{us}| &= 0.2252, |V_{ts}| = 38.7 \times 10^{-3}, \gamma = (67.2 \pm 3.9)^\circ, &(5)\\ |V_{ub}| &= 3.89 \times 10^{-3}, |V_{tb}| = 0.88. &(6) \end{aligned}$$

In the B-rest frame, the decay rates of $B \to a_1(b_1)K^*$, can be written as

$$\Gamma = \frac{G_F^2(1 - r^2_{a_1(b_1)})}{32\pi M_B} \sum_{\sigma=L,N,T} \mathcal{M}^{\sigma\dagger}\mathcal{M}^\sigma, \tag{7}$$

where $\mathcal{M}^\sigma$ is the total decay amplitude of each considered decay. The subscript σ is the helicity states of the two final mesons with one longitudinal component and two transverse ones. The decay amplitude can be decomposed into three scalar amplitudes a, b, c according to

$$\begin{aligned} \mathcal{M}^\sigma &= \epsilon^*_{2\mu}(\sigma)\epsilon^*_{3\nu}(\sigma)\left[a g^{\mu\nu} + \frac{b}{M_2M_3}P_B^\mu P_B^\nu + i\frac{c}{M_2M_3}\epsilon^{\mu\nu\alpha\beta}P_{2\alpha}P_{3\beta}\right]\\ &= \mathcal{M}_L + \mathcal{M}_N\epsilon^*_2(\sigma = T)\cdot\epsilon^*_3(\sigma = T) + i\frac{\mathcal{M}_T}{M_B^2}\epsilon^{\alpha\beta\gamma\rho}\epsilon^*_{2\alpha}(\sigma)\epsilon^*_{3\beta}(\sigma)P_{2\gamma}P_{3\rho}, \end{aligned} \tag{8}$$

where M_2 and M_3 are the masses of the two final mesons $a_1(b_1)$ and K^*, respectively. The amplitudes $\mathcal{M}_L, \mathcal{M}_N, \mathcal{M}_T$ can be expressed as

$$\begin{aligned} \mathcal{M}_L &= a\, \epsilon^*_2(L)\cdot\epsilon^*_3(L) + \frac{b}{M_2M_3}\epsilon^*_2(L)\cdot P_3\epsilon^*_3(L)\cdot P_2,\\ \mathcal{M}_N &= a, \quad \mathcal{M}_T = \frac{M_B^2}{M_2M_3}c. \end{aligned} \tag{9}$$

We can use the amplitudes with different Lorentz structures to define the helicity amplitudes, one longitudinal amplitudes H_0 and two transverse amplitudes $H_\pm$:

$$H_0 = M_B^2\mathcal{M}_L, \quad H_\pm = M_B^2\mathcal{M}_N \mp M_2M_3\sqrt{r^2-1}\mathcal{M}_T, \tag{10}$$

where the ratio $r = P_2 \cdot P_3/(M_2M_3)$. After the helicity summation, we can get the relation

$$\sum_{\sigma=L,N,T} \mathcal{M}^{\sigma\dagger}\mathcal{M}^\sigma = |\mathcal{M}_L|^2 + 2\left(|\mathcal{M}_N|^2 + |\mathcal{M}_T|^2\right) = |H_0|^2 + |H_+|^2 + |H_-|^2. \tag{11}$$

Certainly another equivalent set of helicity amplitudes are often used, that is

$$\begin{aligned} A_0 &= -M_B^2\mathcal{M}_L,\\ A_\parallel &= \sqrt{2}M_B^2\mathcal{M}_N,\\ A_\perp &= M_2M_3\sqrt{2(r^2-1)}\mathcal{M}_T. \end{aligned} \tag{12}$$

Using this set of helicity amplitudes, we can define three polarization fractions $f_{0,\parallel,\perp}$:

$$f_{0,\parallel,\perp} = \frac{|A_{0,\parallel,\perp}|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}. \tag{13}$$

The matrix element $\mathcal{M}_j$ of the operators in the weak Hamilitonian can be calculated by using PQCD approach, which are written as

$$
\begin{aligned}
M_j &= V_{ub}V_{us}^*T_j - V_{tb}V_{ts}^*P_j \\
&= V_{ub}V_{us}^*T_j(1 + z_j e^{i(\gamma+\delta_j)}),
\end{aligned} \tag{14}
$$

where $j = L, N, T$ and γ is the Cabibbo-Kobayashi-Maskawa weak phase angle, defined via $\gamma = arg[-\frac{V_{tb}V_{ts}^*}{V_{ub}V_{us}^*}]$. δ_j is the relative strong phase between the tree and the penguin amplitudes, which are denoted as "T_j" and "P_j", respectively. The term z_j describes the ratio of penguin to tree contributions and is defined as

$$
z_j = \left|\frac{V_{tb}V_{ts}^*}{V_{ub}V_{us}^*}\right| \left|\frac{P_j}{T_j}\right|. \tag{15}
$$

In the same way, it is easy to write decay amplitude $\overline{\mathcal{M}}_j$ for the corresponding conjugated decay mode:

$$
\begin{aligned}
\overline{\mathcal{M}}_j &= V_{ub}^*V_{us}T_j - V_{tb}^*V_{ts}P_j \\
&= V_{ub}^*V_{us}T_j(1 + z_j e^{i(-\gamma+\delta_j)}).
\end{aligned} \tag{16}
$$

So the CP-averaged branching ratio for each considered decay is defined as

$$
\begin{aligned}
\mathcal{B} = (|\mathcal{M}_j|^2 + |\overline{\mathcal{M}}_j|^2)/2 &= |V_{ub}V_{us}^*|^2 \left[T_L^2(1 + 2z_L\cos\gamma\cos\delta_L + z_L^2)\right. \\
&\left. +2\sum_{j=N,T} T_j^2(1 + 2z_j\cos\gamma\cos\delta_j + z_j^2)\right].
\end{aligned} \tag{17}
$$

Like the decays of B to two vector mesons, there are also 3 types of helicity amplitudes, so corresponding to 3 types of z_j and δ_j, respectively. It is easy to see that the dependence of decay width on δ and γ is more complicated compared with that for the decays of B to pseudoscalar mesons.

Using the input parameters and the wave functions as specified in this section, it is easy to get the branching ratios for the considered decays which are listed in Table I, where the first error comes from the uncertainty in the B meson shape parameter $\omega_b = 0.40 \pm 0.04$ GeV, the second error is induced by the hard scale-dependent varying from $\Lambda_{QCD}^{(5)} = 0.25 \pm 0.05$, and the last one is from the threshold resummation parameter c varying from 0.3 to 0.4. In Fig.2, we also show the Cabibbo-Kobayashi-Maskawa angle γ dependence of the branching ratios of decays $B \to a_1 K^*$ and $B \to b_1 K^*$. It is easy to see that the branching ratios of decays $\bar{B}^0 \to a_1^+(b_1^+)K^{*-}$ are more sensitive to the angle γ compared with those of other decays. Several remarks on the numerical results are in order:

- Just like the decays $\bar{B}^0 \to a_1^+\rho^-(a_1^0\rho^0)$, the decays $\bar{B}^0 \to a_1^+K^{*-}(a_1^0\bar{K}^{*0})$ have very different tree contributions (shown in Table II), for one is color allowed and the other is color suppressed. While the former proceed via $b \to d$ transition, where the tree operator contributions are CKM allowed, so the branching ratio of $a_1^+\rho^-$ is much larger than that of the decay $a_1^0\rho^0$ [7]. The latter proceed via $b \to s$ transition, where the tree operator contributions are CKM suppressed, so the decay modes $a_1^+K^{*-}$ and $a_1^0\bar{K}^{*0}$ have the branching ratios in the same order, because their penguin contributions are near each other.

TABLE I: Branching ratios (in units of 10^{-6}) for the decays $B \to a_1(1260)K^*$ and $B \to b_1(1235)K^*$. In our results, the errors for these entries correspond to the uncertainties from ω_B, the QCD scale $\Lambda_{QCD}^{(5)}$ and the threshold resummation parameter c, respectively. For comparison, we also listed the results predicted by QCDF approach [7] and the naive factorization approach [8]. The upper limits of the decays $B \to a_1^- \bar{K}^{*0}, b_1 K^*$ measured by BaBar are also listed.

	This work	[7]	[8]	BaBar
$\bar{B}^0 \to a_1^+ K^{*-}$	$9.9^{+1.6+0.4+3.7}_{-1.1-0.6-3.7}$	$10.6^{+5.7+31.7}_{-4.0-8.1}$	0.92	–
$\bar{B}^0 \to a_1^0 \bar{K}^{*0}$	$7.1^{+1.5+0.4+3.1}_{-0.9-0.6-3.1}$	$4.2^{+2.8+15.5}_{-1.9-4.2}$	0.64	–
$B^- \to a_1^- \bar{K}^{*0}$	$10.8^{+2.0+0.7+4.6}_{-1.4-0.8-4.6}$	$11.2^{+6.1+31.9}_{-4.4-9.0}$	0.51	< 3.3
$B^- \to a_1^0 K^{*-}$	$4.8^{+0.6+0.2+1.6}_{-0.5-0.3-1.6}$	$7.8^{+3.2+16.3}_{-2.5-4.3}$	0.86	–
$\bar{B}^0 \to b_1^+ K^{*-}$	$18.0^{+3.3+1.3+6.3}_{-2.6-2.3-6.3}$	$12.5^{+4.7+20.1}_{-3.7-9.0}$	0.32	< 5.0
$\bar{B}^0 \to b_1^0 \bar{K}^{*0}$	$9.6^{+2.1+1.0+3.8}_{-1.5-1.1-3.8}$	$6.4^{+2.4+8.8}_{-1.7-4.8}$	0.15	< 8.0
$B^- \to b_1^- \bar{K}^{*0}$	$23.0^{+4.5+2.3+8.4}_{-3.5-2.9-8.4}$	$12.8^{+5.0+20.1}_{-3.8-9.6}$	0.18	< 5.9
$B^- \to b_1^0 K^{*-}$	$10.6^{+1.9+0.7+3.4}_{-1.5-1.4-3.4}$	$7.0^{+2.6+12.0}_{-2.0-4.8}$	0.12	< 6.7

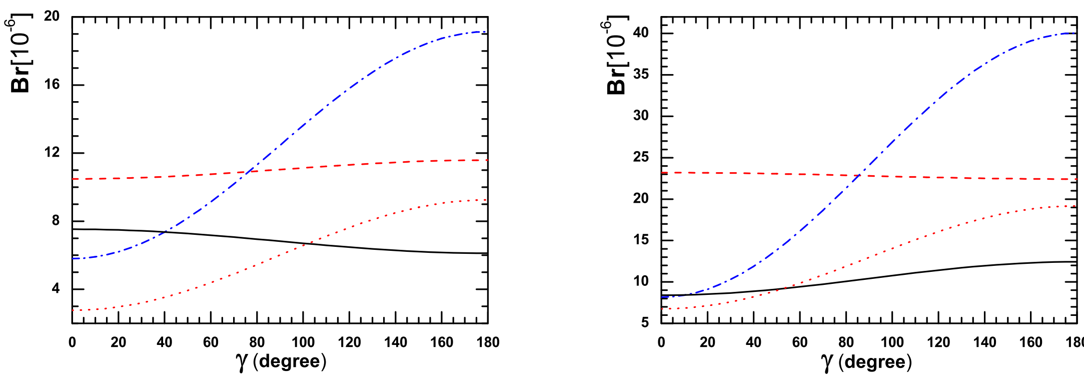

FIG. 2: The dependence of the branching ratios on the Cabibbo-Kobayashi-Maskawa angle γ. The left (right) panel is for the decays $B \to a_1(b_1)K^*$. The dotted line represents the decays $B^- \to a_1^0(b_1^0)K^{*-}$, the solid line represents the decays $\bar{B}^0 \to a_1^0(b_1^0)\bar{K}^{*0}$, the dashed line is for the decays $B^- \to a_1^-(b_1^-)\bar{K}^{*0}$, the dot-dashed line is for the decays $\bar{B}^0 \to a_1^+(b_1^+)K^{*-}$.

- In our prediction, the branching ratio of the decay $\bar{B}^0 \to a_1^0 \bar{K}^{*0}$ is larger than that of the decay $B^- \to a_1^0 K^{*-}$, it is mainly induced by the amplitudes of factorizable emission diagrams 1(a) and 1(b) F_{ea_1} and F_{eK^*} (for the corresponding exchange diagrams) have contrary interference effects between these two decays : constructive for the decay $a_1^0 \bar{K}^{*0}$, destructive for the decay $a_1^0 K^{*-}$. So the the decay $\bar{B}^0 \to a_1^0 \bar{K}^{*0}$ receives a larger real part for the penguin amplitudes. Though the decay $B^- \to a_1^0 K^{*-}$ has much larger contributions from tree operators, which are CKM

TABLE II: Polarization amplitudes of different diagrams for the decays $\bar{B}^0 \to a_1^+ K^{*-}, a_1^0 \bar{K}^{*0}$ ($\times 10^{-2}\mathrm{GeV}^3$).

Decay mode	Pol. amp.	(a) and (b)	(c) and (d)	(e) and (f)	(g) and (h)
$a_1^+ K^{*-}$	$A(T_L)$	-228.6	$8.5 - 4.3i$	$-$	$-$
	$A(T_N)$	-27.4	$-8.6 + 6.2i$	$-$	$-$
	$A(T_T)$	-68.9	$-15.5 + 3.9i$	$-$	$-$
	$A(P_L)$	9.1	$-0.1 + 0.1i$	$0.3 + 0.4i$	$-1.0 - 4.4i$
	$A(P_N)$	1.0	$0.3 - 0.2i$	$-0.03 - 0.01i$	$1.0 + 4.1i$
	$A(P_T)$	2.7	$0.6 - 0.1i$	$-0.06 - 0.02i$	$1.1 + 7.8i$
$a_1^0 \bar{K}^{*0}$	$A(T_L)$	-16.3	$-12.7 + 3.2i$	$-$	$-$
	$A(T_N)$	-2.6	$5.3 - 1.5i$	$-$	$-$
	$A(T_T)$	-5.4	$10.8 - 1.7i$	$-$	$-$
	$A(P_L)$	-8.3	$0.3 - 0.2i$	$0.2 - 0.3i$	$2.2 + 3.1i$
	$A(P_N)$	-1.0	$-0.3 + 0.3i$	$0.02 + 0.00i$	$-0.6 - 2.9i$
	$A(P_T)$	-2.5	$-0.6 + 0.1i$	$0.04 + 0.01i$	$-0.4 - 5.5i$

suppressed and can not change the branching ratio too much.

- In order to characterize the contribution from tree operators and symmetry breaking effects between B^- and $\bar{B}^0$ mesons, it is useful to define the two ratios:

$$R_1 = \frac{\mathcal{B}(B^- \to a_1^- \bar{K}^{*0})}{\mathcal{B}(\bar{B}^0 \to a_1^+ K^{*-})} \times \frac{\tau_{\bar{B}^0}}{\tau_{B^-}}, R_2 = \frac{\mathcal{B}(B^- \to b_1^0 K^{*-})}{\mathcal{B}(\bar{B}^0 \to b_1^+ K^{*-})} \times \frac{\tau_{\bar{B}^0}}{\tau_{B^-}}. \tag{18}$$

If one neglects tree operators and electro-weak penguins, the ratios obey the limit

$$R_1 = 1, R_2 = 0.5. \tag{19}$$

Here the two ratios R_1 and R_2 are predicted as 1.02 and 0.55, respectively. It is to see that the two ratios predicted by QCDF are 0.98 and 0.52, respectively. If the future data for R_1 have large deviation from our value, the contribution from electro-weak penguin operators might give an important affect, for the contribution from tree operators can not change the branching ratio of $\bar{B}^0 \to a_1^+ K^{*-}$ too much. If the future data for R_2 have large deviation from our calculation value, some mechanism beyond factorization even from new physics might give an important affect, because the factorizaton formulae between $\bar{B}^0 \to b_1^+ K^{*-}$ and $B^- \to b_1^0 K^{*-}$ are exactly the same with the neutral b_1^0 meson decay constant vanishing.

- Compared with other results: From Table I, One can find that our predictions are consistent well with the QCDF results within (large) theoretical errors, while in stark disagreement with the naive factorization approach. Our predictions are much larger than the results calculated by Calderón, Muñoz and Vera [8], where the nonfactorizable effects are described by the effective number of colors N_c^{eff}. For some decays, where the contributions from the emission diagrams are dominated or

TABLE III: Branching ratios (in units of 10^{-6}) for the decays $B \to a_1(1260)K^*$ and $B \to b_1(1235)K^*$. The label -Nonfac. Anni. and -Fac. Anni. mean the results with neglecting the nonfactorization and factorization annihilation diagrams, respectively. The label -Anni. means the results with neglecting all the annihilation type contributions.

	Full contributions	-Nonfac. Anni.	-Fac. Anni.	-Anni.
$\bar{B}^0 \to a_1^+ K^{*-}$	9.9	10.3	5.2	5.4
$\bar{B}^0 \to a_1^0 \bar{K}^{*0}$	7.1	7.4	5.0	5.2
$B^- \to a_1^- \bar{K}^{*0}$	10.8	11.0	6.7	8.4
$B^- \to a_1^0 K^{*-}$	4.8	4.9	2.1	2.1
$\bar{B}^0 \to b_1^+ K^{*-}$	18.0	19.0	8.5	9.0
$\bar{B}^0 \to b_1^0 \bar{K}^{*0}$	9.6	10.2	4.5	5.1
$B^- \to b_1^- \bar{K}^{*0}$	23.0	23.6	10.9	12.4
$B^- \to b_1^0 K^{*-}$	10.6	10.9	4.8	5.0

the branching ratios have a strong dependence on the correlative form factors, the naive factorization approach can give a reasonable prediction, while for the decays, where the annihilation diagrams play an important role, this approach would expose some disadvantages. BarBar has been searched the decays $B \to a_1^- \bar{K}^{*0}, b_1 K^*$ and set the upper limits on their branching ratios ranging from 3.3 to 8.0×10^{-6} at the 90% confidence level [9, 10]. Our predictions are (much) larger than the upper limits. It is noticed that these upper limits are obtained by assuming that $\mathcal{B}(a_1^{\pm} \to \pi^+\pi^-\pi^{\pm}) = \mathcal{B}(a_1^{\pm} \to \pi^0\pi^0\pi^{\pm})$ and $\mathcal{B}(a_1^{\pm}(b_1^{\pm}) \to \rho^0(\omega)\pi^{\pm}) = 1$. The current data seem to imply that penguin annihilation is small in these penguin-dominated decays. Certainly, if one neglects the contributions from the nonfactorizable annihilation diagrams, the branching ratios only have a tiny increase, while if the factorizable annihilation diagram contributions are neglected, the branching ratios will fall dramatically and many of them reduced by more than half (shown in Table III). It needs further accurate experiments to clarify the differences between the theoretical predictions and the present upper limits.

To resolve the $B \to \phi K^*$ polarization puzzle surges a considerable amount of theoretical attentions: The author in Ref.[20] considered two class new-physics four-quark operators, namely $(1 \pm \gamma_5) \otimes (1 \pm \gamma_5)$, $\sigma(1 \pm \gamma_5) \otimes \sigma(1 \pm \gamma_5)$, which could account for the data. While the author in Ref. [21] proposed to take a smaller $B \to K^*$ form factor and strengthen the penguin annihilation and nonfactorizable contributions, which could be achieved simultaneously by adopting the asymptotic models for the K^* meson distribution amplitudes. Here we take the second suggestion and find that the polarization charactors for decays $B \to a_1 K^*$ and $B \to b_1 K^*$ are very different: the transverse polarization amplitudes have almost equal values with (even a little stronger than) the longitudinal polarization ones for the former, while the longitudinal polarization states are dominated for the latter. It seems that the similar anomalous polarizations occured in decays $B \to \phi K^*, \rho K^*$ also happen in decays $B \to a_1 K^*$, while not happen in decays $B \to b_1 K^*$. Here we find that the contributions from the annihilation diagrams are very important to the

TABLE IV: Longitudinal polarization fraction (f_L) and two transverse polarization fractions ($f_\parallel$, $f_\perp$) for the decays $B \to a_1(1260)K^*$ and $B \to b_1(1235)K^*$. In our results, the uncertainties come from ω_B, the QCD scale $\Lambda^{(5)}_{QCD}$ and the threshold resummation parameter c. The results of f_L predicted by the QCDF approach are also displayed in parentheses for comparison.

	$f_L(\%)$	$f_\parallel(\%)$	$f_\perp(\%)$
$\bar{B}^0 \to a_1^+ K^{*-}$	$48.9^{+5.1+7.4+4.9}_{-4.7-8.0-4.9}(37^{+39}_{-29})$	$26.1^{+2.5+3.8+2.6}_{-2.8-4.1-2.6}$	$25.0^{+2.2+3.8+2.3}_{-2.3-3.5-2.3}$
$\bar{B}^0 \to a_1^0 \bar{K}^{*0}$	$59.6^{+4.7+7.7+4.3}_{-4.9-7.8-4.3}(23^{+45}_{-19})$	$20.2^{+2.6+3.8+2.2}_{-2.5-3.8-2.2}$	$20.2^{+2.3+4.0+2.1}_{-2.2-3.5-2.1}$
$B^- \to a_1^- \bar{K}^{*0}$	$50.3^{+5.1+8.6+5.0}_{-4.9-9.9-5.0}(37^{+48}_{-37})$	$24.1^{+2.6+5.0+2.5}_{-2.7-3.7-2.5}$	$25.6^{+2.3+5.0+2.5}_{-2.4-4.9-2.5}$
$B^- \to a_1^0 K^{*-}$	$49.0^{+3.3+6.2+4.7}_{-4.3-6.2-4.7}(52^{+41}_{-42})$	$25.5^{+2.3+0.0+2.4}_{-2.5-2.5-2.4}$	$25.5^{+2.0+3.2+2.2}_{-2.2-3.7-2.2}$
$\bar{B}^0 \to b_1^+ K^{*-}$	$95.9^{+0.1+1.1+0.0}_{-0.1-1.3-0.0}(82^{+18}_{-41})$	$1.1^{+0.2+0.4+0.2}_{-0.0-0.2-0.2}$	$3.0^{+0.0+0.9+0.2}_{-0.1-0.7-0.2}$
$\bar{B}^0 \to b_1^0 \bar{K}^{*0}$	$95.4^{+0.1+1.0+0.1}_{-0.1-1.4-0.1}(79^{+21}_{-74})$	$0.9^{+0.0+0.2+0.4}_{-0.0-0.2-0.4}$	$3.7^{+0.1+1.2+0.3}_{-0.1-0.8-0.3}$
$B^- \to b_1^- \bar{K}^{*0}$	$96.2^{+0.0+0.9+0.1}_{-0.0-1.7-0.1}(79^{+21}_{-74})$	$1.0^{+0.0+0.3+0.3}_{-0.0-0.3-0.3}$	$2.8^{+0.0+0.9+0.2}_{-0.0-0.6-0.2}$
$B^- \to b_1^0 K^{*-}$	$96.5^{+0.0+0.8+0.1}_{-0.1-1.3-0.1}(82^{+16}_{-26})$	$0.7^{+0.1+0.2+0.2}_{-0.0-0.1-0.2}$	$2.8^{+0.0+0.9+0.3}_{-0.0-0.6-0.3}$

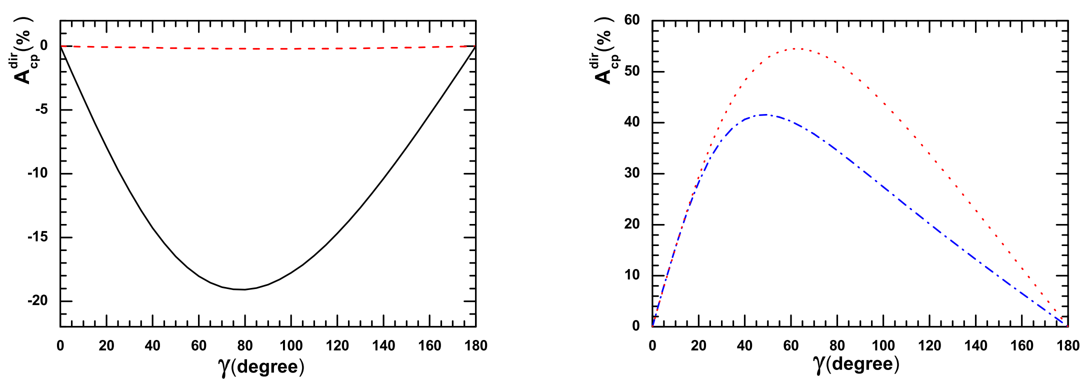

FIG. 3: Direct CP-violating asymmetry as a function of Cabibbo-Kobayashi-Maskawa angle γ. The dashed line is for the decay $B^- \to b_1^- \bar{K}^{*0}$, the solid line represents the decay $\bar{B}^0 \to b_1^0 \bar{K}^{*0}$, the dotted line represents the decay $B^- \to b_1^0 K^{*-}$, the dot-dashed line is for the decay $\bar{B}^0 \to b_1^+ K^{*-}$.

final polarization fractions for the decays $B \to a_1 K^*$: If these contributions are neglected, the longitudinal polarization fraction of the decay $B^- \to a_1^0 K^{*-}$ becomes 98.8%, those of $\bar{B}^0 \to a_1^+ K^{*-}, a_1^0 \bar{K}^{*0}$ increase to about 90%, that of the decay $B^- \to a_1^- \bar{K}^{*0}$ changes from 50.3% to 70.0%. While the longitudinal polarizations of decays $B^- \to b_1^- K^{*-}$ and $\bar{B}^0 \to b_1^+ K^{*-}, b_1^0 \bar{K}^{*0}$ only have a very small decrease by neglecting the annihilation type contributions. That of the decay $B^- \to b_1^- \bar{K}^{*0}$ has a larger amplitude reduction, changing from 96.2% to 86%. In a word, the longitudinal polarizations of decays $B \to b_1 K^*$ are not sensitive to the annihilation type contributions.

Now we turn to the evaluations of the CP-violating asymmetries in PQCD approach. Here we only research the decays $B \to b_1 K^*$, where the transverse polarization fractions are very small and range from 3.8 to 5.2%. Using Eq.(14) and Eq.(16), one can get the expression for the direct CP-violating asymmetry:

$$\mathcal{A}_{CP}^{dir} = \frac{|\overline{\mathcal{M}}|^2 - |\mathcal{M}|^2}{|\mathcal{M}|^2 + |\overline{\mathcal{M}}|^2} = \frac{2z_L \sin\alpha \sin\delta_L}{(1 + 2z_L \cos\alpha \cos\delta_L + z_L^2)} \, . \tag{20}$$

Here for our considered four decays, the contributions from the transverse polarizations are very small, so we neglected them in our calculations. Using the input parameters and the wave functions as specified in this section, one can find the PQCD predictions (in units of 10^{-2}) for the direct CP-violating asymmetries of the considered decays:

$$\mathcal{A}_{CP}^{dir}(\bar{B}^0 \to b_1^+ K^{*-}) = 38.5^{+1.2+8.8+4.5}_{-1.7-7.4-4.5}, \tag{21}$$

$$\mathcal{A}_{CP}^{dir}(B^- \to b_1^0 K^{*-}) = 54.3^{+0.9+7.8+4.4}_{-1.7-6.7-4.4}, \tag{22}$$

$$\mathcal{A}_{CP}^{dir}(\bar{B}^0 \to b_1^0 \bar{K}^{*0}) = -18.7^{+2.0+0.7+1.8}_{-1.3-0.3-1.8}, \tag{23}$$

$$\mathcal{A}_{CP}^{dir}(B^- \to b_1^- \bar{K}^{*0}) = -0.18^{+0.23+0.47+0.33}_{-0.28-0.00-0.33}, \tag{24}$$

where the errors are induced by the uncertainties of B meson shape parameter $\omega_b = 0.4 \pm 0.04$, the hard scale-dependent varying from $\Lambda_{QCD}^{(5)} = 0.25 \pm 0.05$, and the threshold resummation parameter c varying from 0.3 to 0.4. It is particularly noteworthy that our predictions about the direct CP asymmetries of these decays are consistent well with the QCDF results [22] :

$$\mathcal{A}_{CP}^{dir}(\bar{B}^0 \to b_1^+ K^{*-}) = (44^{+3}_{-58})\%, \tag{25}$$

$$\mathcal{A}_{CP}^{dir}(B^- \to b_1^0 K^{*-}) = (60^{+6}_{-73})\%, \tag{26}$$

$$\mathcal{A}_{CP}^{dir}(\bar{B}^0 \to b_1^0 \bar{K}^{*0}) = (-17^{+21}_{-10})\%, \tag{27}$$

$$\mathcal{A}_{CP}^{dir}(B^- \to b_1^- \bar{K}^{*0}) = (2^{+0}_{-2})\%, \tag{28}$$

where the error comes from the parameters $\rho_{A,H}$ and arbitrary phases $\phi_{A,H}$. These are phenomenological parameters to cure the endpoint divergences in the amplitudes for the annihilation and hard spectator scattering diagrams. Just because of cannot calculating the annihilation and hard spectator scattering diagrams accurately, there are large theoretical errors for the QCD factorization predictions.

IV. CONCLUSION

In this paper, by using the decay constants and the light-cone distribution amplitudes derived from QCD sum-rule method, we research $B \to a_1 K^*, b_1 K^*$ decays in PQCD factorization approach and find that

- Our predictions for the branching ratios are consistent well with the QCDF results within errors, but much larger than the naive factorization approach calculation values. BarBar has searched the decays $B \to a_1^- \bar{K}^{*0}, b_1 K^*$ and set the upper limits for their branching ratios, which are (much) lower than our predictions. The current data seem to imply that penguin annihilation is small in these penguin-dominated

decays. Certainly, if the factorizable annihilation diagram contributions are turned off, the branching ratios will fall dramatically and many of them reduced by more than half. It needs further accurate experiments to clarify the differences between the theoretical predictions and the present upper limits.

- we predict that the similar anomalous polarizations occured in decays $B \to \phi K^*$ also happen in decays $B \to a_1 K^*$, while not happen in decays $B \to b_1 K^*$. Here still the contributions from the annihilation diagrams play an important role to explain the lager transverse polarizations in decays $B \to a_1 K^*$, while are not sensitive to the polarizations in decays $B \to b_1 K^*$.

- Our predictions for the direct CP-asymmetries agree well with the QCDF results within errors. The decays $\bar{B}^0 \to b_1^+ K^{*-}, B^- \to b_1^0 K^{*-}$ have larger direct CP-asymmetries, which could be measured by the present LHCb experiments.

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